Review of South African research on volcanic and related rocks and mantle -derived materials: 1999-2002

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This report reviews South African research relating to the scientific interests of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and which was published between in 1999 through 2002. The focus is on published research and does not include conference presentations and abstract volumes or other informal documents. As a previous National Correspondent[1] has noted it is not easy to determine what precisely is covered by "South African research" and the "scientific interests of IAVCEI". In compiling this report, one approach I could have adopted would be to include all research of any igneous or volcanic flavour. Another is to aim at comprehensive coverage but to select on the basis of research results which I perceive to be of interest to the broader IAVCEI membership. As an example, consider an Archaean pyroclastic deposit. A paper focused on the description and emplacement of the deposit would clearly fall within the interests of IAVCEI. If the deposit has been tectonized and metamorphosed and is mentioned briefly in a paper whose main focus is the dating of zircons recovered from the unit, then it is legitimate to consider the paper to have little relevance to global IAVCEI membership. However, the timing of volcanism and associated igneous activity in relation to tectonism is of considerable interest to our understanding of temporal trends in global volcanism and tectonics, a topic falling within the broad interests of IAVCEI members and, on balance, might be included in the report to IAVCEI. In this context this review does report on papers concerned with dating of volcanic and igneous rocks.

Apart from research on volcanic rocks and associated intrusions this review also reports on inclusions of deep origin contained in kimberlite and other rare alkaline rocks as they are a rich source of information on the chemistry of the Earth's interior. Work carried out by South African-based scientists in contiguous countries as well as in the oceanic environment surrounding South Africa is also covered. I have not reported research on South African rocks carried out exclusively by scientists based in other countries, as this work is expected to be reflected by the reports from the National Correspondent of those countries. Much of such work is, however, published in collaboration with South African scientists and is included here.

Most of the material in the report is organized according to geological time periods starting with the Archaean. The exceptions are carbonatitic and kimberlitic rocks and associated materials which are discussed together regardless of age. Some published research has probably been inadvertently omitted, but for some the omission is on the basis of a judgement of relevance. Such omissions are minor and do not detract from the overall impact of this review as a statement of the research achievements of South African scientists from 1999 to 2000.

Archaean Greenstones, Komatiites, and Granitoid rocks

These are complex entities involving volcanism and plutonism and allied structural deformation and metamorphism. Much of the research carried out is by necessity of a multidisciplinary nature, including age dating.

The 3.48 Ga Komati Formation Barberton was mapped by Dann[2] on a scale of 1:5 000 with special attention to detailed mapping of chill-bounded cooling units and to defining volcanic, intrusive and tectonic contacts. This mapping allowed the magmatic architecture of the Komati Formation to be established. The formation consists of a lower sequence of komatiitic sheet flows emplaced in a lava-plain setting, followed by pillowed komatiites emplaced in a more irregular topographic environment, possibly caused by faulting. The sequence is intruded by pyroxene-spinifex-textured sills, but the wherlite dykes are younger than the Komati and overlying Hoogenoeg Formations. Thus the komatiites do not have a feeder dyke system analogous to post-Archaean ophiolites. Cloete [3] also gives a detailed account of the volcanology and geochemistry of the komatiitic eruptives and concluded that they have attributes akin to modern oceanic plateaux rather than typical mid ocean ridge crust. His work is also concerned with primary sea floor alteration of the komatiites.

Anhaeuser [4] argues that the more metamorphosed komatiites and komatiitic basalts of the Nelshoogte Schist Belt and associated intrusions represent a younger (ca 3250 Ma) ultramafic volcanic event and he also rejects previous proposals that these rocks are similar to Phanerozoic ophiolites.

A number of studies report single zircon ages for a variety of granitic rocks in the greenstone belts. These ages are important in providing a temporal framework for the evolution of the belts. Hence Poujol and Robb[5] demonstrate that the granitic magmatism was contemporaneous with the deposition of the 3-09-2.97 Ga Murchison greenstone belt and extended to younger ages of 2.85 Ga. This was subsequently extended to an even younger age of 2680 Ma[6]. In the Pietersburg greenstone terrane felsic volcanism is dated at 2949.7 +/- 0.2 Ma[7] indicating that it is coeval with felsic volcanism in the Murchison Belt to the east. A granite intruding the greenstone is dated at 2853 +/- 18 Ma. In addition, the associated Turfloop Batholith was emplaced at about 2.78 Ga on the basis of U-Pb, Sm-Nd and Rb-Sr dating [8] and has an origin in the lower Archaean crust. In the Amalia-Kraaipan greenstone belt in the western Kaapvaal craton, the earliest tonalites and trondhjemites as varying in age from 3162+/-8 to 3070+/-7 Ma and the youngest pluton , the Mosita adamellite, is dated at 2749+/-3 Ma[9]. In the same area, Poujol et al.[10] have dated granite magmatism varying from ca 3008 Ma (trondhjemitic) to 2791 Ma (granodioritic). These new results suggest a temporal correlation of the youngest granitoid activity with the emplacement of the Gaborone Granite Complex in Botswana. In the Giyani greenstone belt meta andesites have yielded an age of 3203.3+/-0.2 Ma and younger intrusive quartz porphyries have an age of 2874.1+/- 0.2 Ma [7]. In the Johannesburg Dome a variety of trondhjemitic and granitic rocks yield single zircon U/Pb ages from 3340+/-3 Ma in the north to 3114+/-2.3 Ma in the S[11]. Similar age ranges were obtained using a variety of dating techniques by Barton et al [12].

Archaean Supracrustal Sequences

The oldest supracrustal sequence in the Kaapvaal craton is the Pongola Supergroup with a lower Nsuze Group of volcanic and sedimentary rocks and an overlying siliclastic Mozaan Group. Gutzmer et al.[13] report an age of 2837+/- 5 Ma for quartz porphyry sill intruded into these sediments and deformed with them.

The Late Archaean Ventersdorp Supergroup continues to attract attention. It consists of basal formations of mafic lava overlain by a clastic wedge deposit, the Kameeldoorns Formation, which formed in grabens. Intermediate to felsic ash-flow deposits of the Makwassie and Goedgenoeg Formations overlie these sediments. Large spherical structures and clasts have been described at the base of the Makwassie Formation at T'kuip in the Northern Cape Province[14] and are ascribed to eruption of the hot ash-flow onto water-saturated sediments. De Bruiyn et al. [15] also report on the geochemistry of alteration of andesitic and basaltic andesite lavas of the uppermost Allanridge Formation. Such studies are important for effective use of geochemistry in petrogenetic studies on these old sequences. Hall and Els [16] report on lava - soft sediment interactions at the base of the Ventersdorp Supergroup. Features such as sediment injection into lava, "ball and pillow" structures in lava, and soft sediment deformation are described. These features developed during dewatering of the sediments in response to differential loading of the sediments by the overlying lava.

The Palaeoproterozoic

Oberholzer and Eriksson[17] describe the volcanic sequence in the Palaeoproterozoic Hekpoort Formation of the Transvaal Supergroup as consisting of equal volumes of basaltic-andesite lava flows and intercalated with volcaniclastic rocks emplaced in a subaerial intracratonic setting. The volcaniclastic rocks are thought to represent a variety of pyroclastic flow and laharic deposits. In a paper which is significant for correlation of the Kheis and Magondi mobile belts as components of a extensive Palaeoproterozoic orogen in southern Africa, McCourt et al.[18] report an age of 1997.5 +/- 2.6 Ma for the syn kinematic Hurungwe granite, Zimbabwe. This age invalidates the Kheis -Magondi correlation.

The Bushveld Magmatic Province

The Bushveld Complex is purported to be the largest continental layered mafic-ultramafic intrusion (Rustenberg Layered Suite) and is associated with coeval mafic and silicic volcanic suites (the Rooiberg Group) and intrusive granites (Lebowa Granite Suite). Collectively these suites form the Bushveld Magmatic Province. The enormous metal reserves (platinum group elements (PGEs), Cr, Ti, Fe) in the complex has ensured that it is the target of much research. The South African Journal of Geology published two Special Issues largely relating to the Bushveld Complex. The first, edited by Cawthorn[19], commemorated the 75th anniversary of the discovery of the Merensky Reef, and the second, edited by Maier [20], was directed at Platinum group minerals and elements. Not all of the papers in these two volumes fall within the interests of IAVCEI

Bushveld magmatism was initiated by eruption of basaltic andesites and felsic volcanic rocks of the Dullstroom Formation, the lowest formation of the Rooiberg Group. Buchanan *et al.* [21] demonstrate that the mafic rocks can be divided into a high- and low-Ti lineage with strong compositional similarities to the Mesozoic Karoo flood basalt geochemical types. They suggest that a mantle plume was responsible for the mafic volcanism and present petrogenetic models involving magma mixing and assimilation to account for the compositional variability. Associated high-Mg felsic rocks in the Dullstroom Formation, as well as siliceous to intermediate rocks in the upper part of the Rooiberg Group, are derived from the low-Ti mafic magmas by assimilation of crustal material and fractional crystallization (AFC) in shallow magma chambers [22].

Maier *et al.* [23] use the PGE geochemistry of the ultramafic Pyroxenite Marker within the mafic Main Zone of the Bushveld complex to constrain a model for the formation of this zone. In a study using mineral composition reversal and whole-rock compositional trends within the vicinity of the Pyroxenite Marker, Nex *et al.* [24] examine the processes of magma addition to the Main Zone. The transition from the Critical to Main Zones is believed to exist in the vicinity of the Giant Mottled Anorthosite but has not been pinpointed precisely. Mitchell and Manthree [25] investigate this problem and develop a model for the emplacement of the Main Zone.

The Merensky Reef in the top of the Critical Zone is arguably the most famous horizon within the Bushveld Complex. A number of papers [26,27,28,29,30,31,32] address problems of geology, mineralogy, and geochemistry of the reef and discuss implications for its origin. The development of cyclic units in the Critical Zone below the Merensky Reef is ascribed by Cawthorn [33] to crystal sorting during settling.

In broader studies, Maier and Barnes [34] analyzed for PGEs in a wide range of silicate rocks through the complex in an attempt to constrain ore forming processes within the intrusion. Eales [35] examined the Cr budget in the western Bushveld and demonstrated that the amount of chromite in the rocks exceeds the Cr solubility of mafic magmas and suggests that the magmas emplaced into the Bushveld chamber were carrying up to 3% chromite as microphenocrysts. Willmore *et al.* [36,37] have investigated halogen geochemistry of the Bushveld and identify correlations of Cl/F ratio with a number of geochemical and mineralogical trends through the complex. Bushveld magmas appear to have been unusually enriched in Cl, and all evidence points to the halogens being a primary magmatic component and not derived by assimilation of, or infiltration from, country rocks. Separation of Cl-rich fluids have played a role in mineralization in the Lower and Critical Zones. This is supported by chlorine isotopes . Maier *et al.* [38] report on a wide ranging Nd-isotope study of the Bushveld complex which supports older Sr-isotope data indicating a large crustal component in the upper part of the intrusion. The isotopic data are decoupled from highly incompatible element concentrations. This is interpreted in terms of changes in the nature of the crustal assimilant with evolution of the complex. Contamination by crust, including unusual compositions such as dolomite, are also indicated in the work of Harris and Chaumba [39] on the Platreef in the Northern Limb of the Bushveld Complex.

A structural study relating to mechanisms of intrusion of the Rustenberg Layered Suite along its southwestern margin (Spruitfontein Inlier) was documented by Clarke *et al.* [40] .

Discordant ultramafic iron-rich pegmatoidal bodies are common in the Rustenberg Layered Suite and their origin and petrogenesis is controversial. A detailed study [41] on the Tweefontein pipe indicates that it was magmatically intruded when the layered rocks were still extremely hot and that it is a magmatic as opposed to metasomatic feature. The pipe magmas are not residual liquids derived from adjacent layered rock, but distinct magma batches in their own right. Reid and Basson [42] focused on similar bodies replacing the Merensky Reef at Northam Platinum Mine. They conclude that the pegmatoid bodies result from replacement of pre-existing rocks by residual melts migrating from the upper Critical Zone. Scoon and Eales [43] showed that spinels in the pegmatoids can be divided into three types and that there is a relationship between spinel type and stratigraphic height. The composition of the Fe-Ti-Cr spinels is not duplicated by cumulus spinels in the layered rocks but the disseminated Ti-magnetites are very similar to that found in the Upper Zone.

Minor intrusions associated with the Bushveld Complex include the Uitkomst Complex and numerous mafic-ultramafic sills in the footwall of the Bushveld Complex. Using olivine compositions and sulphur isotopes Li *et al.* [44] present a model for multiple intrusion emplacement of the Uitkomst complex which is consistent with it being a conduit to the Bushveld Complex as proposed by Gauert [45] . Age and geochemical similarities between the Uitkomst complex and a diorite intrusive into the Marble Hall fragment suggest that there is a genetic link between the two and has led De Waal and Armstrong [46] to define a new magma type (Bu-type) which preceded the emplacement of the Bushveld B1-type magma and which may also have been significant in a number of sub-Rustenberg Layered Suite intrusions such as the Lindequesdrift, Roodekraal, and Rietfontein complexes. The nature of the Bushveld magmas is also discussed by Eales [47]. Maier *et al.*[48] discuss PGE mineralization of ultramafic footwall sills exposed around the eastern margin of the complex.

Maier and Barnes [49] investigate the origin of the Cu-sulphide deposits associated with mafic-ultramafic intrusive bodies, 2.0-2.3 Ga in age, in the Curaçá Valley, Brazil. These intrusions have been emplaced in a high-grade metamorphic terrane and as such resemble the O'okiep deposits in western South Africa.

Although strictly an Archaean intrusion, research on the Great Dyke of Zimbabwe is reported here because of its similarities to the Bushveld Complex. Wilson and Prendergast [50] have reviewed the magma evolution and magma chamber structure of the Great Dyke with emphasis on implications for PGE mineralization. In more detail Wilson [51] and Wilson *et al.* [52] report on geology, mineralogy and geochemistry of the Selukwe subchamber of the Great Dyke, Zimbabwe. The zone of PGE enrichment is associated with sharp compositional changes in orthopyroxene, and the layered subzones, characterized by different PGE contents, may reflect original liquid layering in the chamber.

Mesoproterozoic

Research results are of two types - petrogenetic studies on igneous intrusions and volcanic sequences and dating of intrusive and extrusive rocks with the aim to constrain correlations and the tectonic and metamorphic evolution of mobile belts. In the latter category fall the work of Gutzmer *et al.*[53] on the Koras bimodal volcanic suite and Mendonidis *et al.*[54] on the Glenmore granite, Kwazulu-Natal South Coast. Petrogenetic studies include that of Kruger *et al.*[55] who describe the petrology and geochemistry of the 1.1 Ga Oranjekom Complex of layered gabbronorites and anorthosite. The Oranjekom magmas were derived from a depleted mantle source and were Al-rich. Differentiation took place by sorting of mafic phases with plagioclase remaining largely suspended. Evans *et al.* [56] investigated the petrogenesis of the 1.0 Ga Tete complex in NW

Mozambique. Magmas forming this complex were also derived from depleted mantle sources with little evidence of crustal contamination and were emplaced at shallow levels in the upper crust with differentiation to form gabbroic, pyroxenitic and anorthositic rocks. Maier *et al.* [57] repot on PGE-mineralization in this complex

South African-based scientists have also been involved in research related to the 1.33 Ga Voisey's Bay troctolite-gabbro intrusion and associated Ni-Cu-Co sulphide deposits in Canada. These involve Nd-Sr-Pb isotopes and crustal assimilation [58], melting of gneiss inclusions in the ore-associated breccia [59], comparison of Voisey's Bay and the Mushuau intrusion [60], the oxygen isotope geochemistry of Voisey's Bay intrusion [61], the oxygen fugacity during sulphide segregation [62], and the Re-Os isotope systematics of the intrusion with implications for parental magma chemistry and ore genesis [63].

Neoproterozoic.

Research on Neoproterozoic rocks essentially concerns granite magmatism, especially the precise dating of magmatic activity. In South Africa Frimmel *et al*. [64] report ages ranging from 833+/-2 Ma through to 741+/-6Ma for various components of the felsic extrusive and intrusive Richtersveld Igneous Complex, northwestern South Africa. This magmatism developed in accordance with crustal thinning over a mantle plume. Also in this area are the post-orogenic alkaline granites of the Kuboos-Bremen line of intrusions trending NE from northwest South Africa into southern Namibia. One of the largest plutons is the Kuboos pluton which intrudes the Pan-African Gariep belt whose main phase of deformation occurred at 545+/-2 Ma. Frimmel *et al*.[65] reports a U/Pb age of 507+/-6 Ma for the youngest intrusive phase of this pluton. Scheepers and co-workers have focused on the 515-552 Ma Cape granite suite intrusive into the Pan-African mobile belt in the south western part of the Western Cape Province. They report broadly synchronous SHRIMP ages of 547+/-6 Ma for the early syntectonic Darling granite and 536+/-5 Ma for the post-tectonic Robertson granite [66]. Nd isotopes suggest that both granites were derived form Mesoproterozoic crustal sources. This range of ages for granite activity was extended by subsequent SHRIMP age determinations on 3 granites comprising the Saldanha batholith, believed to be amongst the oldest of the Cape Granite Suite [67]. Ages obtained range from 552+/-4 Ma to 539+/-4 Ma . Scheepers and Nortje [68] describe rhyolitic ignimbrites at Postberg, associated with the Saldanha batholith and Scheepers and Pojoul [69] discuss their geochemistry and petrogenesis and demonstrate by a single zircon age of 515+/- 3 Ma that they represent the final phase of Cape Granite suite magmatism. A detailed petrogenetic study of the Malmesbury batholith was published by Siegfried[70]. He showed that the batholith is built of seven granitoid intrusions derived largely from a mafic igneous source by fractional crystallization with crustal assimilation.

Further afield, Handke *et al.* [71] report U-Pb zircon and baddeleyite ages of 804-779 Ma for 11 coeval gabbroic and granitoid intrusions of along a 450 km belt in Madagascar. Yibas *et al.* [72] report U-Pb ages of 880-526 Ma granitoids in Ethiopia. In a petrogenetic study Harris and Ashwal [73] report results of an O-isotope study on the 750 Ma Seychelles granites indicating that the Mahé types was derived from juvenile mafic to intermediate crust, whereas the Praslin type was derived from a source which was a mixture of this crust and older crust which acquired its low $d^{18}O$ significantly before granite genesis.

Mesozoic Volcanism

Karoo Flood Basalt Province

Most publications focus on the intrusive element of this classic continental flood basalt province (CFB). Chevallier and Woddford [74] analyzed a large amount of field data for 3 sill-ring complexes in the western Karoo basin, South Africa. They show that these structures are complex and built of stacked saucer-like intrusions (inclined sheets) interlinked with flat inner and outer sills and arcuate dykes. Their work shows that emplacement of these complexes is initiated from dykes which feed the inclined sheets. These then propagate into the outer sill and then into the inner sill. The implications are that the sheets are an integral part of the feeding system to the subaerial lavas.

In an analysis of magma flow directions at the mineralized Insizwa intrusion using the AMS technique, Ferre *et al*. [75] show that magnetic and mineral lineations coincide and represent magma flow directions. Furthermore, the intrusion is built by multiple injection events from a lower level located to the SE of the Insizwa massif. In a paper focused on the Ni-Cu-PGE potential of Insizwa, Maier *et al*. [76] show that the magmas feeding the intrusion were depleted in PGE before emplacement and contained no entrained sulphide. They indicate little potential for an economic deposit associated with Insizwa. Expanding this work to the lavas of the Karoo province and other CFB sequence of all ages in southern Africa, these authors [77] find that all the flood basalts are depleted in PGE relative to Cu, except the oldest (Dominion, Ventersdorp). They conclude that the data are consistent with minor sulphide segregation during ascent and that these CFBs have to be considered poor exploration targets.

The behaviour of lava flows is addressed by De Bruiyn *et al.*[78] who present evidence of flow concentration of olivine phenocrysts in a basalt flows high in the sequence in Lesotho to produce a picritic core to the flow. Such evidence is important in accounting for olivine-rich layers within large differentiated intrusions such as Insizwa. In the Sabie River Formation in the northern Lebombo the occurrence of peperite in the upper margin of a basalt sheet is interpreted as a shallow sheet that has burrowed into unconsolidated water-saturated sediment [79]. It is suggested that sediment-impregnated blocky flow tops that occur elsewhere in the Karoo volcanic sequence might have a similar origin. Weinert and Dunlevey [80] report the first recorded occurrence of the zeolite yugawaralite in Karoo basalts of the southern Lebombo.

Etendeka Igneous Province

Marsh *et al*. [81] reviewed decades of research on the Etendeka Group, Namibia, which is equivalent to the Paraná Province in South America. On the basis of geochemistry they define eight mafic and seventeen silicic magma types and describe their areal and stratigraphic distribution. There is a marked but not exclusive geochemical provinciality within the Etendeka Province with incompatible element enriched (high-Ti) mafic and silicic rocks having a close geographic association as do the low-Ti mafic and silicic rocks. The Doros complex is shown to the eruptive site of the early Tafelkop basalts which have affinities to the Tristan Plume. Comparisons with the Paraná indicate that all the important silicic types in the Paraná have geochemical equivalents in the Etendeka, hence extending the previous the trans-Atlantic correlations of the two provinces. These correlations indicate that volumetrically giant silicic systems developed with pronounced lithospheric thinning and rifting in continental flood basalt provinces.

Associated with the Etendeka flood volcanism are a large number of cental volcanic complexes. One of these, Messum, has been subjected to detailed studies. Ewart *et al.* [82] showed that the complex igneous geology at Messum is best interpreted as a downsag cauldron subsidence which is distinctly different to the classic cauldron subsidence structures found in the western USA. Focusing on the alkaline rocks in the core of the complex, Harris et al. [83] show that trends towards silica oversaturated syenites reflect crustal contamination of nepheline-bearing parental magmas. Basanite dykes are isotopically similar to the modern Tristan lavas and may reflect an input from the Tristan plume into the complex.

Other Mesozoic igneous suites.

As part of the South African Earth Sciences Research Programme in Antarctica, Harris et al. [84] discuss the petrogenesis of he largest Mesozoic intrusion in Dronning Maud Land, Antarctic - the Sistefjell Syenite which is associated with the 'Karoo' CFB igneous event in that continent. Major, trace, radiogenic and stable isotope data indicate that the composition variation in the syenite is consistent with fractional crystallization with some contamination by the metamorphic basement and the low d^{18}O Sistenup lavas of unknown age. Harris also contributed to the understanding of the large-volume rhyolitic volcanism in Patagonia and the Antarctic Peninsula [85] which parallels the palaeo-Pacific margin of Gondwana.

Cenozoic to Recent Volcanism

Ocean Island volcanism

Harris *et al*. [86] discuss oxygen isotopes measured on phenocryst in lavas from those Tristan Da Cunha and Gough Island basalts which have enriched isotopic signatures. For Gough Island the phenocrysts are in isotopic equilibrium and suggest that the least evolved magmas had the same O isotopic composition as MORB and that more evolved lavas evolved by closed system fractional crystallization. At Tristan, O-isotopes ratios are lower suggesting that material from the volcanic edifice contaminated the parental mafic magmas. The most primitive lavas evolved by AFC involving crystal accumulation, but the evolved lavas evolved by closed system fractional crystallization.

Mid-Ocean Ridge volcanism

In a series of papers, Le Roux *et al.* [87,88,89] describe the geochemistry and petrogenesis of MORB erupted along the southern Mid Atlantic Ridge (MAR) 40 - 55 degrees . This part of the MAR is moderately slow-spreading and lies in the vicinity of the Discovery and Shona mantle plumes. There are systematic distribution of E-MORB and N-MORB on the ridge with the former related to the proximity of the mantle plumes. The basalts also exhibit mild geochemical signatures of subduction. A model involving interaction in the melting regime of the mantle plumes, delaminated continental lithosphere from Gondwana break-up, and subduction contaminated asthenospheric mantle is proposed. Along this segment the source in the vicinity of the Discovery plume has greater proportions of clinopyroxene. Partial melting (15-17%) at 18 Kb produces N-MORB whereas slightly higher degrees of melting at slightly higher pressures characterize melting in the vicinity of the plumes. Subsequent evolution of melts involve crystallization of olivine, plagioclase and clinopyroxene. Crystallization of N-MORB occurred at pressures of 3-6 Kb whereas that in the plume-influenced melts occurred over a greater pressure range (1 atm -7Kb, but predominantly at 1 atm -3Kb). These differences are ascribed to higher temperatures, more constant magma fluxes and increased longevity of subaxial magma chambers in the vicinity of mantle plumes.

Continental Rift Volcanism

Spath *et al.* [90,91] and Le Roex *et al.* [92] report on geochemical studies of volcanoes on the flanks of the southern Kenya rift (Chyulu Hills 10 km E of the rift) and from the rift walls and floor (Lake Magadie area). The Chyulu Hills volcanoes range in composition from nepheline-normative nephelinites, basanite, and hawaiites to orthopyroxene-normative subalkali basalts. Compositions are consistent with olivine-dominated differentiation. Spatial and temporal variations in degree of silica-undersaturation is explained in terms of variation in depth and degree of melting. The striking geochemical feature in these lavas is their depletion in K in mantle-normalized trace element plots; this is explained in terms of residual amphibole in the melting regime. This is turn implies a source in the lithosphere which is metasomatized by a rising mantle plume to be followed later by melting. Similarly the mildly nepheline-normative within-rift alkali basalts and basanite are generated by variable amounts of melting to depths extending into the garnet stability field and in the presence of residual amphibole, again suggesting melting in the sub-continental lithosphere rather than in the asthenosphere or rising mantle plume. The lithosphere must extend to depths of 75 km beneath the Magadie area.

Anorogenic alkaline volcanism

Using the South Western Cape melilitite-alkali basalt province (76-58 Ma) Janney *et al.* [93] demonstrate that strong trace element and isotopic variations correlate with lithospheric thickness. Eruptives on the continental shelf have strong HIMU affinities whereas those on thick Proterozoic lithosphere have EM 1 isotopic features and kimberlite-like trace element patterns. A complex two-stage mixing process is used to account for the data and it is proposed that unlike oceanic areas where the HIMU component is supplied from a conventional mantle plume, under Africa the HIMU component is in pods of recycled oceanic crust incorporated in a laterally broad, long-lived upwelling.

Carbonatites

Reviewing Sr and Nd-isotope composition of carbonatites, Harmer [94] compares these to kimberlites and argues that CO_2-rich residues forming from ponded kimberlites rise from the base of the lithosphere and are trapped at the peridotite-CO_2 thermal maximum at 2 GPa and enrich the lithospheric peridotite there. This enriched peridotite forms the source for subsequent carbonatitic magmas. Ionov and Harmer [95] report results of laser-ablation ICPMS trace element determinations in calcite-dolomite carbonatites with well-preserved igneous textures from Spitskop. Calcite phenocrysts have low REE and flat patterns in comparison with interstitial late-crystallizing calcite which is strongly enriched in LREE . This suggests that REE are incompatible during fractional crystallization of carbonatite liquids. The phenocryst abundances are similar to carbonates in mantle xenoliths indicating that the latter are crystal cumulates rather than quenched carbonatite liquids. In a paper focusing on potassic trachytes, the only significant silicate rock of the Dicker Willem carbonatite, Namibia, Cooper and Reid [96] show that the trachytes are isotopically similar to the highest grade of potassic fenites associated with the carbonatite. They propose that the trachytes are partially melted fenites.

Kimberlites and mantle materials

In 1998 the 7th International Kimberlite conference took place in Cape Town and a two volume set of papers relating to that meeting was published in 1999 [97] . Other publications on this topic have appeared in numerous journals.

Kimberlites

In more general studies on the origin of kimberlite magma, Sweeney and Winter [102] integrate results from high pressure experimental petrology and major element composition of kimberlite to constrain the depth of melting and the residual mineralogy of the source. Nowell *et al.* [103] adopts and isotopic approach offering an Hf -isotope perspective on components contributing to both Group I and II kimberlite magmas. They recognize a negative ?eHf component which they propose derives from a deep sub-lithospheric source. Kimberlite magmas are generated in a plume derived from this deep source and attain additional isotopic variability by assimilating variably enriched lithospheric mantle.

Several descriptions of individual kimberlite pipes in southern Africa [104,105] and Australia [106,107] are also reported.

Xenocrysts

Field and Scott-Smith [98] present a comprehensive review of the geology of kimberlite pipes, reviewing the standard model which was established from observations on South African pipes and comparing it to others in southern Africa and the newly-discovered pipes in Canada. They review and redefine terminology and demonstrate the variability of pipes in terms of pipe shape and internal geology. They demonstrate relationship between pipe type and the nature of the country rocks and discuss implications for emplacement mechanisms. Emplacement mechanism is also a concern of Rice [99] who has applied engineering studies on blasting to understanding kimberlite eruption mechanisms.

Skinner *et al.* [100] address the controversial topic of the presence of melilite in kimberlite and shows that it is present in most Group II kimberlites and in some phlogopite-rich Group I kimberlites. Crystallization is favoured in the diatreme facies as a consequence of CO_2 loss. Recognition of late-crystallizing phases which formed subsequent to melt degassing is important for Ar-Ar dating of kimberlite as shown by Phillips *et al.* [101] who success fully applied laser probe step-heating analysis to single groundmass phlogopite and K-richterite grains in eleven kimberlites in South Africa.

Xenocrysts, including diamond and its inclusions, have proved to be fertile sources for information about the Earth's interior. The 240 Ma Jwaneng pipe in Botswana is one of the few where diamonds with an eclogitic inclusion assemblage (eclogitic diamonds) occur[108]. These inclusions yield a Mesoproterozoic (1580 Ma) Sm-Nd isotope age, similar to that obtained from Finsch eclogitic diamonds, and initial Nd-isotopic composition indicative of derivation from a depleted mantle source. The Jwaneng and Finsch results point to a regional eclogitic diamond formation event in the Mesoproterozoic Proterozoic related to interaction between subducted lithosphere with the stable Archaean lithosphere.

Viljoen *et al*. [109] and Aulbach *et al.* [110] reviewed the inclusions in diamonds from the Venetia pipes which are important as they have an unusual and somewhat anomalous location in the Limpopo Mobile Belt at the junction of the Kaapvaal and Zimbabwe cratons. The most common inclusion type is sulphide with peridotitic oxide and silicate inclusions and minor eclogitic and websteritic types. Mineral chemistry suggests diamond crystallized at 900^{o}-1400^{o}C at 55-70 Kb in a thick ancient cratonic root dominated by highly-depleted magnesian peridotite. Results for websteritic and eclogitic inclusions are consistent with eclogite representing subducted ocean crust whereas the websterites represent the product of reaction of slab-derived melts with mantle peridotite. Viljoen [111] reports on infrared studies on diamonds from the Venetia kimberlite. Nitrogen contents and nitrogen aggregation states are highly variable with unusually high aggregation in the majority of diamonds - making it unusual when compared to the cratonic kimberlite localities in southern Africa. High aggregation is a feature of other craton margin localities world-wide. Deformation in the mantle is thought to accelerate nitrogen aggregation in the diamonds.

Descriptions of inclusions in diamond from a craton-margin kimberlite, Dokolwayo, Swaziland, are reported by Daniels and Gurney [112] . They report a variety of inclusions (peridotitic assemblages predominating) with variable composition recording macro- and micro-scale geochemical heterogeneity in the mantle where the diamonds formed. Among the inclusions is staurolite which has implications for the high-P stability of this mineral. They also discuss the carbon isotopic composition of a suite of 88 diamonds from Dokolwayo [113], the majority of which lie with the normal range, regardless of their eclogitic or peridotitic character. The carbon source is considered to be methane which degassed from the lower mantle or core. Grutter *et al.* [114] have surveyed the composition of xenocrystic peridotitic garnets occurring on a regional scale on the Slave craton, Canada. Using the Cr_2O_3-CaO relationships as an indicator of depletion, they show that there are marked differences across at least three distinct northeast-trending lithospheric domains which are not reflected in isotopic compositions of Archaean crustal rock, suggesting isotopic decoupling between crust and mantle. For South Africa these authors demonstrate significant compositional differences in the lithospheric mantle on either side of the wrench-fault system that defines the the SW margin of the Kaapvaal craton. Towards the centre of the craton lithospheric thickness is correlated with geochemical signatures of melt depletion in peridotite which imparts stability to thickened cratonic roots.

Xenoliths

Xenolith studies encompass thermobarometry, whole rock major and trace element geochemistry, and isotope geochemistry. Girnis *et al.* [115] carried out experiments in the FMASCr system to derive internally consistent thermobarometers for spinel and garnet harzburgites and apply the results to touching and non-touching inclusions in diamond. Tainton *et al.* [116] applied garnet thermobarometry to garnets recovered from a number of intrusions in the Central Tanzanian Craton and define heatflow patterns within this craton. In a detailed description of the xenolith suite from Venetia, South Africa, Stiefenhofer *et al.* [117] show that the suite is dominated by peridotites with pyroxenite and demonstrate that they have been affected by melt-metasomatism. Thermobarometry reveals the presence of a high-temperature inflection in the Venetia geotherm. In Namibia non-kimberlitic mantle xenoliths have been recovered from a ca 75 Ma nephelinite[118] at Swakopmund and from a lamprophyre pipe at Okenyenya[119] both sited on the Damara Mobile belt between the Congo and Kaapvaal cratons. Refractory and fertile peridotite xenoliths are present, the latter representing a variety of mantle not previously documented in southern Africa. They define a hot geotherm which probably relates to regional Cretaceous magmatism associated with the opening of the south Atlantic ocean.

Van Achterbergh *et al.* [120] have estimated the element fluxes during metasomatism of a suite garnet-bearing mantle xenoliths from the Letlhakane kimberlite, Botswana. They show that modally metasomatized rocks become enriched in Sr, Na, K, LREE. And Ti, Zr, and Nb, with the removal of Al, Cr, and Fe and garnet-compatible trace elements are removed. The proposed depletion in Al challenges a previous view that the metasomatic environment was merely Al-poor.

Gregoire *et al.*[121] re-examine the occurrence of the two phlogopite-bearing xenolith suites, MARID and PIC, and demonstrates that the two are clearly distinguished in terms of major and trace element compositions of common minerals and Sr and Nd-isotopes. Moreover geochemical data indicate a genetic relationship of the xenolith types to Group I kimberlites (PIC) and Group II kimberlites (MARID). In a detailed textural compositional and oxygen isotope study Zhang *et al.*[122] interpret the ilmenite-rich ploymict mantle xenoliths from Bultfontein as precipitates from a Fe-Ti-Cr-rich melt which in turn could have separated through immiscibility of a migrating high-Ti silicate melt. Carlson *et al.*[123] present new and review previously published Re-Os isotopic data for peridotite xenoliths in southern Africa. Menzies *et al.* [124] report additional data for the Newlands peridotites. Overall the Kaapvaal craton peridotites Re-depletion ages in the early Proterozoic to late Archaean, and they have the lowest $^{187}Os/^{186}Os$ of any terrestrial rock.

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